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Review on Solar Cooling Technologies used Under Middle East Climate

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***Abstract*:- The use of solar cooling systems to save energy, reduce moisture from the air and to improve indoor air quality is found to be economic and environmental friendly due to their superior humidity control. Their basic characteristic refers to their capability of regulating temperature, humidity and the quantity of fresh air supplied to any conditioned space and also the using solar energy as a prime driving medium.**

This article presents an extended overview of solar assisted air conditioning technologies. The conceptual basis of the technologies, capabilities and limitation are discussed. Afterwards the fundamental and theories involved with solar energy and solar collector's technologies are summarised and discussed.

Key words: Solar cooling, HVAC, Energy

1 INTRODUCTION

Buildings, considered as one of the most important infrastructure sectors in modern society. On the other hand commercial buildings consume a considerable amount of energy which has direct impacts on the environment. In fact this leads to a significant greenhouse gas emissions and production of non environmental materials. Hence global warming is the most common dilemma facing the world governments at the present time. Burning of fossil fuels to generate electricity has contributed to Australia having the highest greenhouse gas (GHG) emissions per capita in the developed world. Building air conditioning in Jordan consumes a significant amount of electricity which is produced by burning coal and fossil fuel. At the same time, most of the institutional buildings are using air conditioning economisers which function based on the usage of recycled air and air ventilation. However, the usage of recycled air will allow viruses, germs, dust and mould transmission. Besides, due to the middle East region's high temperature and high humidity, fungus and mould growth have always been a problem within institutional buildings. In high humidity climates, humidity is a major factor to be considered when designing heat, ventilation and air conditioning systems (HVAC) for energy efficiency. Replacing conventional cooling systems with ones powered by solar energy can be the ultimate solution of the fossil fuel energy dilemma.

The use of solar desiccant cooling systems to save energy, reduce moisture from the air and to improve indoor air quality is found to be economic and environmental friendly due to their superior humidity control. Their basic characteristic refers to their capability of regulating temperature, humidity and the quantity of fresh air supplied to any conditioned space.

2. SOLAR COOLING TECHNOLOGIES

The idea of air conditioning started in the year 1848 when Johne Gorrie constructed an ice making machine with a fan to blow air on the ice in order to cool down the hospital rooms where malaria and yellow fever patients were treated (Gladstone, 1998). In the year 1881, the U.S. naval engineers constructed an expensive cooling system for the dying president of the U.S. James Garfield which consisted from a box containing a cloth saturated with melted ice and a fan blew hot air overhead. This mechanism was able to reduce the room temperature by nearly 11 °C. The invention high cost was due to the big amount of melted ice used in the process. It was estimated that, the system consumed half a million pounds of ice in two months. A similar to today's air conditioning systems was made in the year 1902 by Willis Carrier. The cooling system was named the Apparatus for Treating Air [1].

Auguste Mouchout has developed a steam engine driven by a solar parabolic collector to produce a block of ice in the year 1878 for Paris Exhibition. The invention was consist of a mirror over 3.96 meters in diameter and 79.5 litters boiler as shown in Figure 2.19 [2].

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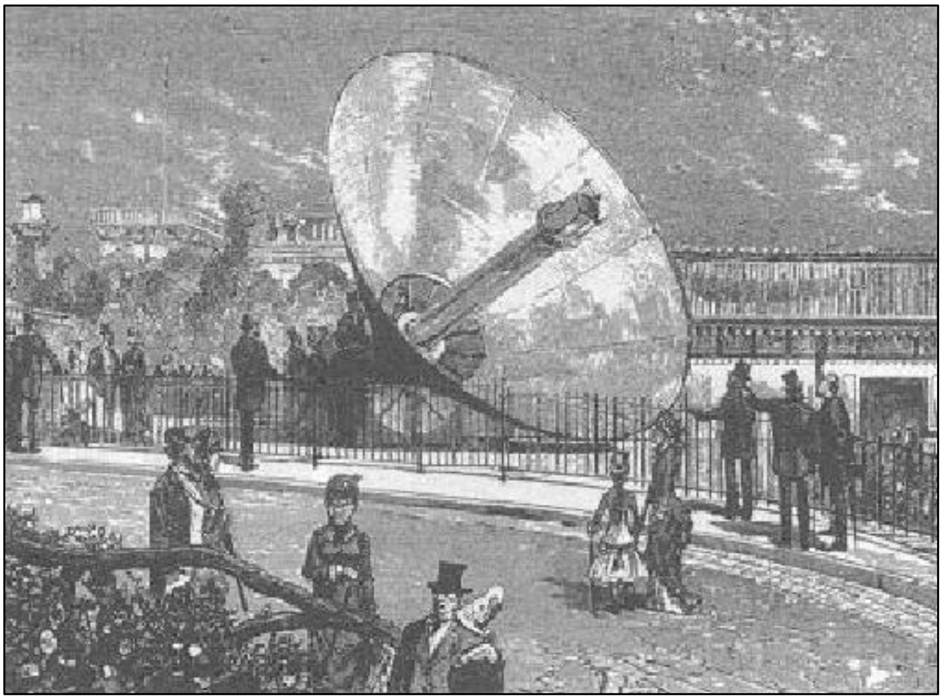

Figure 2.1: Block of ice solar generation 1878 by Mouchout (SEAI, 2010)

According to [3], deployment of solar cooling technologies in indoor thermal comfort took a place during the 80s of the last century especially on the United State of America and Japan. Since then there are many activities in this field have been started. These activities include researches and demonstration projects in many countries around the globe. The surge of this technology in the recent years was due to the combination of environmental consciousness and fossil fuels soaring prices. Compare to conventional cooling systems, there are a small numbers of solar HVAC systems installed around the world. The majority of these projects are in Europe, Middle East, Australia and the Mediterranean islands. It has been reported that, in the year 2011 there were about 750 solar assisted air cooling systems installed worldwide including small cooling capacity 5 kW and high cooling capacity up to 1470 kW [4].
The majority of these installed solar cooling systems are absorption cooling systems which accounted for 70% of total installed systems followed by solid desiccant systems, adsorption systems, liquid desiccant systems and others at 14%, 13%, 2% and 1% respectively as described in Figure 2.20. It is worthy to mention, solar assisted air conditioning industry worldwide leader is the International Energy Agency (IEA). The organisation was established by multinational body in the year 1974 in order to improve the performance of several energy technologies. Hence Solar Heating and Cooling Program was one of the first programs that the organisation has investigated and researched.

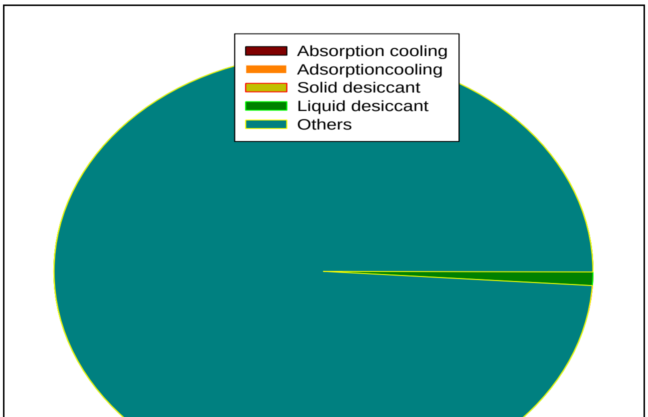

Figure 2.2: Solar cooling technologies by categories(Mugnier, 2010)

(Henning, 2007) has classified solar cooling systems into two categories: solar electric process using solar photovoltaic and solar thermal process using solar thermal collectors.

3. Solar electric (Photovoltaic) cooling systems

This type of solar cooling is conventional cooling system e.g. vapour compression cooling system powered by photovoltaic (PV) cells as shown in Figure 2.21. In general PV panels provide power for any type of electrically driven cooling system. Furthermore, it is mostly implemented with compressors based cooling systems which considered as the least efficient type of electrical cooling systems [5]. Solar photovoltaic cooling techniques are suitable for domestic and small commercial cooling applications or for those applications required cooling capacity less than 5 kWh. One of the main advantages of using photovoltaic for cooling and refrigeration is the cooling system installation simplicity. Solar electric cooling and refrigeration systems are designed and fitted on independent operation and packaged containers.

Thermoelectric coolers which are made of semiconductors are another sort of cooling and refrigeration can be powered by photovoltaic. Thermoelectric coolers are suitable for applications with low cooling capacity (under 25 W) [6]. As these types of coolers have no moving parts or refrigerants and can be made very small and insensitive to motion or tilting, it is suitable to be used in electronic chips cooling and in portable refrigerators similar to ones used in space applications.

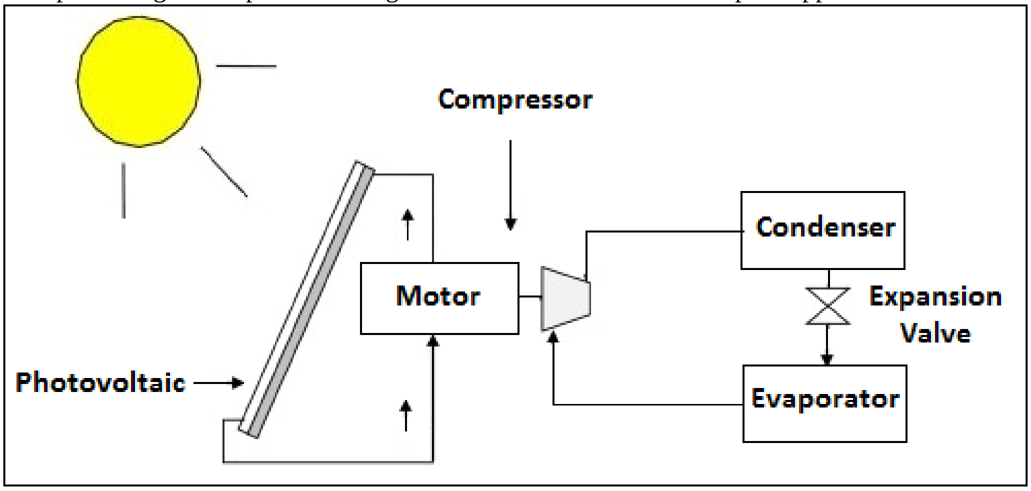

Figure 2.3: PV cooling process (Kim et al., 2008)

Moreover Stirling refrigerators can be powered by solar PV panels to provide cooling. However it is very difficult to develop efficient Stirling cooler. These types of coolers' major problems are their low *COP* and the limited cooling capacity due to the poor heat transfer between the working fluids and surroundings [7].

Electrically driven thermo acoustic cooling systems are another technology can be powered by PV panels. In this technology cooling is achieved by pressure changes in acoustic waves which lead to transfer heat between two channels at different temperatures. Thermo acoustic cooling system has no moving parts and low cooling capacity. Hence no machine has been reported with a suitable large capacity for air conditioning. In addition, the major disadvantages of this systems is there efficiencies which are too low (American Institute of Physics, 2004).

There are several research studies concerning the above cooling technologies, worth mentioning [7-8] have investigated a small cooling capacity of a 100 W with piston free Stirling cooler. [9] and have investigated a similar system in term of its coefficient of performance (*COP*). [7-10] have tested the performance of a refrigeration system with a cooling capacity of 119 W designed for ice cream cabinet have researched Magnetic cooling technology.

However, due to photovoltaic cells high cost, low efficiency and subsequently high price of PV electricity conversion, these systems are not cost effective.

3.1 Solar thermally driven cooling systems

In thermally driven solar cooling systems, solar heat which is produced by solar thermal collectors is used to drive the cooling process. Thermally driven cooling systems have been used for many years, but they have been driven by industrial processes' waste heat. Lately, demonstration projects worldwide have proved the potential of using solar thermal energy to drive cooling process. Normally solar thermal cooling systems are available on a very large cooling capacity. Now a day and due to solar thermal collectors decreasing costs and the increase in their efficiency, the challenge is to develop smaller cooling systems (under 10 kWh) as well as to improve systems performance. Solar thermal cooling system consists of: solar collectors, hot water storage, pipes, pumps, and a thermally driven cooling machine. The cooling application driving temperature is normally below 250 °C. The most common used solar collectors are flat plate collectors, evacuated tube collectors and parabolic through collectors. According to [6], solar thermally driven cooling systems are classified into two groups: thermo mechanical process group and heat transformation process group.

3.2 Solar thermo mechanical process technologies

The main principle of solar thermo mechanical cooling technology is that, a heat engine converts solar thermal energy (heat) to mechanical work, which will drive a conventional cooling system such as vapour compression cooling system. A schematic diagram of such cooling system is shown in Figure 2.22.

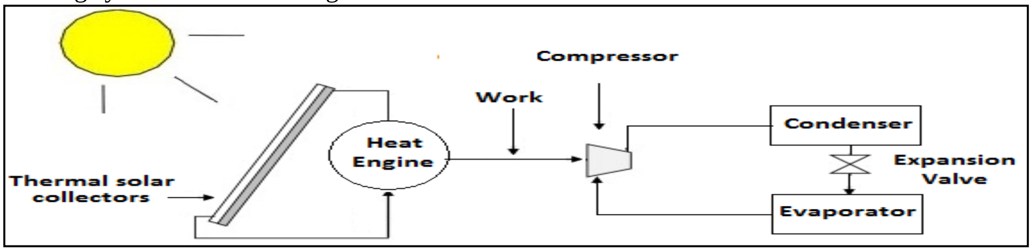

Figure 2.4: Solar thermo-mechanical cooling system (Kim et al., 2008)

In this type of cooling systems a thermal solar collectors convert sun radiation into heat. This heat is then directed into a heat engine to produce mechanical work. Then the mechanical work drives a vapour compressor to remove heat from a conditioned space.

The most known cooling applications belong to solar thermo mechanical cooling technology are Rankine cycle based cooling systems and Ejector based cooling systems (steam ejector**).** Market available solar thermo mechanical cooling systems are available in big cooling capacities. Thus such system is suitable for large air conditioning applications.

3.3 Ejector cooling systems

Ejector cooling systems are similar to conventional vapour compressor based cooling systems. The difference is that, in Ejector cooling systems, the compressor is replaced with the ejector which is considered as a thermally driven compressor that operates in a heat pump cooling cycle. According to (ANU: Solar Thermal Group, 2012), Ejectors have been known prior to 1900. In 1901 Ejector cooling cycle was introduced by Le Blanc and Parsons when they successfully produced a refrigeration cycle using an ejector powered by heat energy [10]. Ejector systems use heat produced by thermal solar instead of electricity to compress a refrigerant without using any moving parts. Hence the compression effect is vibration free. Besides vibration free advantage, Ejector based cooling systems characterised by their simplicity, low operating and low installation cost and their capability of producing cooling from renewable energy resources. However the system biggest disadvantage is its low *COP* which is usually under 0.4.

Solar Ejector based cooling system consists of three circulating loops as shown in Figure 2.24 [8-10]; the solar system phase, ejector power phase and ejector cooling phase. The solar phase consists of a pump, solar collectors and a generator (heat exchanger) to transfer heat to the ejector phase. In solar phase, solar collectors heat the working fluid which is normally water to near 95 °C. Then the heated water leaves the solar collectors to circulate through the generator. The generator transfers heat to the working fluid of the ejector power phase without mixing the two different working fluids flows resulting a high pressure and temperature vapour. An example of the ejector power phase working fluid is halocarbon compounds (Dichlorofluoroethane-R141b). The high pressure refrigerant vapour passes the primary nozzle of the ejector. Then stream accelerates and expands through the ejector to create a low pressure area. This partial vacuum created by the ejector part transferred refrigerant vapour from the evaporator. The evaporator pressure is then reduced and the refrigerant boils causing a low pressure and temperature medium (Meyer *et al.*, 2009).

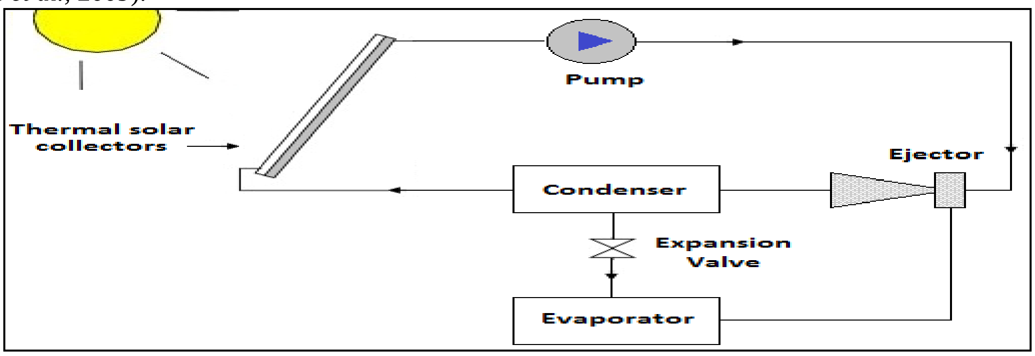

Figure 2.5: Solar Ejector cooling cycle

Over the years there are several research activities concerning solar Ejector cooling systems in order to improve system performance using multi stages ejector or hybrid systems. The first theoretical prediction model was carried out by. In the last decade solar Ejector based cooling systems are investigated extensively due to their simplicity of construction have numerically investigated the performance of a solar ejector cooling system under Turkey climate. has provided an overview concerning two-phase Ejector cooling system's geometry, operation and modelling., have researched a vapour ejector performance taking into account ideal and real gas fluids. In Australia, the Australian National University (ANU: Solar Thermal Group, 2012), are investigating a high performance solar ejector cooling system.

3.4Heat transformation process cooling technologies

To reduce the primary energy consumption by cooling systems, solar thermal heat transformation cooling technologies should be considered. In this type of cooling's technologies, the produced heat by solar collectors is converted directly into cooling using thermally driven air conditioning systems. These systems are functioned based on a physical phenomenon of sorption (sorption process). In general Sorption refrigeration uses a chemical attraction between two substances to produce refrigeration effect.

The main difference between heat transformation process cooling technologies and conventional compression cooling systems is the drive energy. In conventional compression cooling systems the drive energy is electrical or mechanical while in heat transformation process cooling technologies the drive energy is thermal energy which easily can be supplied easily by renewable energy. Hence solar energy is the most available heat source for solar heat transformation process cooling technologies. In addition, this technology is categorised based on the based on the way they control and deliver cooling into conditioned space. Accordingly, solar assisted air conditioning systems are classified into two types: closed systems and open system.

4. ABSORPTION COOLING SYSTEMS

Absorption cooling systems have a great potential to save energy and to minimize buildings' gas emissions. It can be used widely in all kinds of newly constructed or existing older buildings. It is true absorption cooling systems is mature but still the most used system in solar cooling and refrigeration applications. Absorption cooling machines generates cold water from hot water which can be generated by solar thermal collectors.

The thermodynamic cycle of absorption chillers' is normally driven by heat source. In short the main concept behind the function of absorption cycle is based on chemical attraction between two working fluids: the refrigerant and the absorbent. The refrigerant has a lower vapour pressure than the absorbent. Up to date there are two known working fluids used within absorption chillers: lithium bromide (LiBr) pair and ammonia (NH_3) pair. Both working fluids have its advantages and disadvantages as presented in Table 2.6. In lithium bromide (LiBr) pair, LiBr is used as the absorbent while water is the refrigerant. In ammonia (NH_3) pair, NH_3 is the refrigerant and water is the absorbent. Chillers using LiBr pair normally produce water temperature between 5-8 °C while chillers using NH_3 pair are used in special industrial refrigeration and other applications required water temperature under 5°C [11].

Working pair	**Advantages**	**Disadvantages**
$LiBr/H_2O$	• Have a high COP a maximum of 1.2 • Low operation pressure • Non toxic	• Corrosive • Need a vacuum • Crystallization possibility
H_2O/NH_3	• Evaporate below 0 °C • Inexpensive	• Toxic • Need high working pressure • Need rectification

The function of the two types of chillers is similar to conventional cooling system where the role of a mechanical compressor is replaced by a thermal compressor which consists of an absorber, a generator, a pump, a condenser, an evaporator and a circulating valve as schematically shown in Figure 2.25. The absorption cooling cycle starts in the evaporator where the refrigerant evaporates in a low partial pressure environment to the absorber, the evaporation of the refrigerant will causes heat to be extracted from surroundings and cool down the chilled water. Then the gaseous refrigerant is absorbed into other liquid (the absorbent) which causes its partial pressure to be reduced in the evaporator and allowing more liquid to evaporate. The diluted liquid of the refrigerant and the absorbent materials is pumped to the generator where the mixture liquid is heated using heat source (solar and a backup heater) causing the refrigerant to evaporate and then condensed on the condenser (heat exchanger) to refill the supply of liquid refrigerant in the evaporator through a circulation valve. In absorption based cooling systems, liquid circulating pump and the backup heater are operated by electricity. However circulation pumps' energy consumption is too small compared to conventional cooling systems electricity consumption[11-12].

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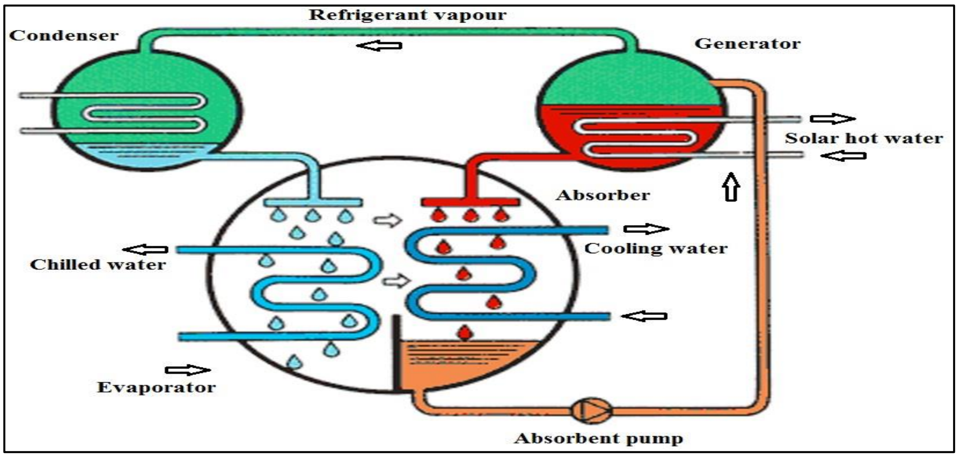

Figure 2.6: A schematic of absorption chiller (Peak Oil, 2012)

Market available absorption cooling technologies is ranging from 50-200 kW with coefficient of performance is ranging from 0.3 to 1.2 as illustrated in Figure 2.26.
Moreover there are two common types of absorption chillers: single affect absorption chillers and double affect absorption chillers. The choice of suitable chillers depends on the type and performance of the used solar collector.

- ***Single effect absorption cooling systems***: cooling cycle driving temperature is ranging between 80-120 ºC. Coefficient of performance is ranging between 0.3 and 0.8.
- ***Double effect absorption cooling systems***: cooling cycle driving temperature is ranging between 120-180 ºC. Coefficient of performance is ranging between 1.0 and 1.3. Double affect absorption cycle is not practical for refrigerants with low boiling temperatures such as ammonia due to the high working pressure.

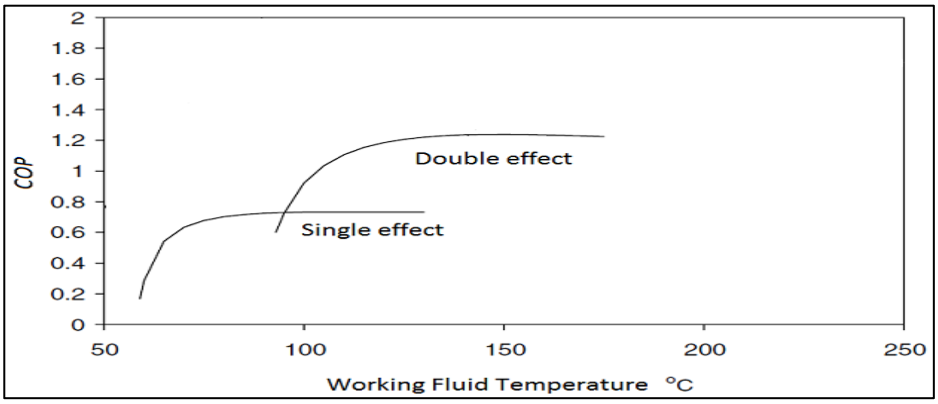

Figure 2.7: Single effect and double effect absorption chiller COP (Eicker, 2009)

The first absorption machine was developed in 1859 by Ferdinand Carre using ammonia NH_3 water refrigeration system . In 1945 Carrier corporation developed the first commercial absorption cooling chiller cooling capacity. In the recent years there are increasing interests in regards searching absorption chillers. The technology has been reviewed by many articles. Among those researchers {10-12] who have reviewed strategies to define new approach and ways to minimize the cost of solar absorption cooling technologies.
However solar absorption chillers have its disadvantages. The most known disadvantages associated with absorption chillers are; they have a low *COP* compare to conventional systems, cannot be used on mobile services, subject to corrosion and they have a very high installation cost.

5. ADSORPTION COOLING SYSTEMS

Adsorption cooling systems are known for their effective cold production which can be easily powered by renewable energy resources. Adsorption chillers are similar to absorption chillers. However in absorption chillers a solution is used to absorb the refrigerant while in adsorption chillers the refrigerant is absorbed by the surface of a highly porous solid. The most known working pairs (absorbent and refrigerant) used within adsorption chillers is water/silica gel, water/ Zeolite, ammonia/ activated carbon or methanol/ activated carbon. Market available machines are only using water/ silica gel pair. Adsorption chillers as shown in Figure 2.27 consist of two compartments where the internal surfaces are covered with silica gel. The sorbent (silica gel) cannot be compressed or pumped. It has to be alternately cooled and heated to be able to adsorb and desorb the refrigerant in a periodic process.

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The cycle starts when the same compartment is heated (regenerated) with the solar hot water at temperatures ranging between 55°C to 95°C. Then the refrigerant at higher temperature moves to the condenser where it is condensed, resulting waste heat that has to be dissipated. The pressure of the condensed water is then dropped using a throttle valve to the same pressure level of the evaporator. At that low pressure, the refrigerant receives enthalpy by the mean of the chilled water and then moving to the other compartment where the silica gel is regenerated by solar heat to complete the process. Adsorption cycle takes around seven minutes and it begins where the refrigerant evaporates in the evaporator with strong vacuum resulting chilled water. Then the refrigerant moves to the other compartments which is containing regenerated silica gel, where it is adsorbed. Then the cool/ hot water cycle inverts. Heat is then supplied to the compartment to regenerate the silica gel. The refrigerant become in pressurised vapour form, and moves to the condenser. The refrigerant condenses in the condenser and the waste heat (to be dissipated) of condensation is removed by cooling water. Liquid refrigerant is then sprayed back to the evaporator to complete the cycle.

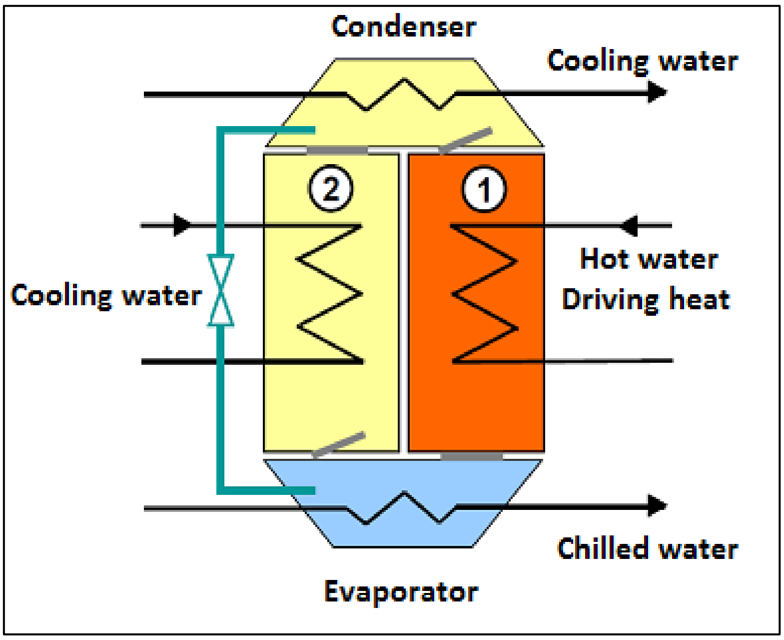

Figure 2.8: Adsorption cooling cycle

Adsorption chillers can be used within industrial air conditioning, process cooling and in commercial buildings as well. Market available absorption cooling technologies is ranging from 50-500 kW with coefficient of performance is ranging from 0.6 - 0.7 (Richler *et al.*, 2002).
Historically, Michael Faraday developed the first adsorption cooling system in 1848 using ammonia/ silver chloride AGCL as a working pair. In 1929, Hulse and Miller developed a refrigeration system using Silica gel/ and sulphur dioxide (SO_2) as a working pair and achieved −12 °C evaporation temperature in order to store food on trains and to be used in the air conditioning systems of railway carriage [10-12]. Lately Adsorption cooling systems have received a significant attention because they are environmentally friendly and they can be powered by low grade thermal energy.
However solar adsorption chillers have its disadvantages. The most known disadvantages associated with adsorption chillers are; there *COP* is small compare to absorption cooling system and conventional systems, it is also cannot be used on mobile services, higher weight in relation to the cooling capacity and they have a very high installation cost.

6. SOLAR DESICCANT SYSTEMS

Solar desiccant cooling systems are considered as an attractive alternative to current conventional cooling systems. The use of solar desiccant cooling systems to save energy, reduce moisture from the air and to improve indoor air quality is found to be economic and environmental friendly. It is also effective when used in hot and humid climates because of their superior humidity control.
The main principle behind desiccant cooling cycle is the system's capability of removing or reducing vapours and moisture out of the treated air using a physical sorption of desiccant materials . Desiccant systems can deliver a dryness enough to treat 7.5 litres of wet air per second per person and personal moisture load of 70W latent (0.1 Litre per hour). Due to desiccant cooling systems basic characteristic in regulating temperature, humidity and fresh air quantity that supplied to any conditioned space. The technology is considered as the most suitable air conditioning systems can be used within commercial buildings, particularly institutional buildings and health care buildings in order to reduce contaminated air transmissions.
Moreover there are two types of desiccant machines: liquid desiccant machines and solid desiccant machines. Both systems are used to improve conventional cooling systems' energy performance and to improve indoor air quality in commercial and residential buildings. There are a range of desiccant materials that can be used in desiccant machines. An examples of these

materials are silica gel, titanium silicates, calcium chloride, activated aluminas, zeolite (natural and synthetic), molecular sieves, lithium chloride, organic-based desiccants, polymers, compound and composite. Market available desiccant systems are liquid spray towers, solid packed tower, rotating horizontal bed, multiple vertical bed and rotating desiccant wheel.

Solar desiccant cooling system consists of three subsystems: solar energy system, the dehumidifier and a cheap cooling technique e.g. evaporative cooler. In solar desiccant cooling system, the cooling process starts in the dehumidifier as explained schematically in Figure 2.28. The untreated supplied air is directed through a desiccant machine which will dry the air. Repeating the process multiple times, the desiccant material will get saturated (wet) and it will lose its sorption characteristics. Drying desiccant materials is performed to drive the moisture out of the desiccant material so it can again absorb moisture and water vapours out of the treated air in subsequent cycles. Drying the desiccant material is called regeneration. The regeneration cycle is done by heating the desiccant material until it reaches its regeneration temperature by using low grade thermal energy resources like solar energy and industrial waste heat.

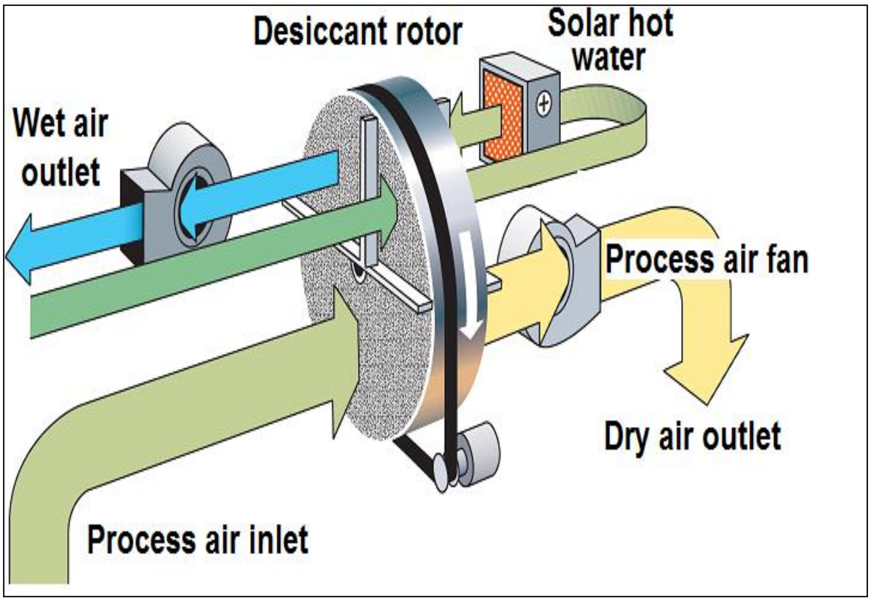

Figure 2.9: Desiccant cooling system operational concept (Baniyounes et al., 2012c)

Solar desiccant cooling techniques have been investigated for several years under various climatic conditions and different comfort level standards. Their energy savings, desiccant effectiveness and indoor air quality have been evaluated and analysed through a number of simulation and experimental studies.

The first to investigate solid desiccant cooling technology was Pennington in 1955 when he presented what known as the Pennington cycle. Recently, there are number of solar desiccant cooling system demonstration projects performed around the word. (Jia *et al.*, 2007) have investigated a solar hybrid desiccant cooling system in subtropical Hong Kong. (Jia *et al.*, 2006) have proved a power saving of 37.5% by using a hybrid solar desiccant cooling system against a vapour compression cooling system under China's hot and humid climate. (Eicker *et al.*, 2009) have investigated different types of commercially available desiccant rotors. (Qi *et al.*, 2012) have analysed an experiment of cooling load profile in commercial building under Hong Kong subtropical climate using desiccant cooling principles. (Ge *et al.*, 2012) have simulated a solar powered desiccant coated heat exchanger cooling system in Shanghai, China. (Enteria *et al.*, 2012) have presented a numerical investigation of a solar desiccant cooling system under the East Asian climates. (Baniyounes *et al.*, 2012c) have investigated the feasibility of the installed Central Queensland University's desiccant cooling system. (Alizadeh, 2008) has tested a solar liquid desiccant cooling system under Brisbane climatic conditions. (Goldsworthy *et al.*, 2011) have analysed the performance of a combined solid desiccant and indirect evaporative cooler. (White *et al.*, 2009) have modelled a solar desiccant cooling system in an office building without thermal backup in three Australian cities: Sydney, Melbourne and tropical Darwin.

7. CONCLUSION

The objective of this study is to present low energy solar cooling technologies which can be applied within institutional buildings in Australian subtropical regions. From the literature there is understanding, that using solar assisted air conditioning will contribute significantly to reduce greenhouse gas emissions, fuel savings and will improve indoor air quality. Besides solar assisted cooling systems are simple technologies that can be integrated with other cooling systems to save energy, improve indoor air quality and minimise gas emission. It is also a growing technology, compared to other fields of solar energy application.

Around the world, the current solar cooling technologies are demonstration projects in nature. Research and development activities are concentrated in improving systems' *COP* as well as making the equipment smaller in size and more affordable.

Due to Australian abundance solar energy, a solar cooling system could meet a large portion of the daily cooling load. Hence Australian are invited to invest more on solar air conditioning techniques despite the fact that solar assisted air conditioning systems are characterised by their high installation costs and the lack of technical information between designers, operators and technicians. Designers, developers and business owners need to break free from only considering its economic aspects and welcome the long run advantages of solar cooling technologies that contribute towards zero emissions buildings and their energy independence. However a reduction in solar cooling equipments manufacturing prices as well as increasing in solar collector's performance will enhance the system feasibility and performance.

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